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Forced convection heat transfer of liquid hydrogen through a 200-mm long heated tube

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Abstract

The heat transfer from the inner side of a vertically- mounted heated tube with a length of 200.0 mm and a diameter of 6.0 mm to a forced flow of liquid hydrogen was measured for wide ranges of flow rate and liquid temperature. The non-boiling heat transfer coefficients agreed well with the Dittus -Boelter equation. The heat fluxes at departure from nucleate boiling (DNB) were higher for higher flow velocities and greater subcooling. The effect of the tube length on the DNB heat flux was clarified through comparison with our previous data. It was confirmed that the experimental data agreed well with the authors' DNB correlation.

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1. Introduction

Liquid hydrogen is expected to find use as a coolant for high- T_c superconducting devices because of its low boiling point (20 K lower than that of liquid nitrogen), high thermal conductivity and large specific heat. So far, there has been a lack of systematic experimental data on forced-flow liquid hydrogen.

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Tatsumoto et al. [1] developed a thermal-hydraulics experimental system for liquid hydrogen in order to carry out a systematic investigation of the forced convection heat transfer of liquid hydrogen. We clarified the effects of the tube diameter and the attitude direction of the heated tube on the forced convection heat transfer, and derived a correlation with the heat flux at departure from nucleate boiling (DNB) based on their experimental data [2-5].

In this study, the forced convection heat transfer of liquid hydrogen passing through a 200-mm-long heated tube with a diameter of 6.0 mm was measured over wide ranges of inlet temperature and flow velocity in order to clarify the effect of the length of the heated tube on the DNB heat flux.

2. Experimental apparatus and method

Details of the experimental system and the measurement procedure have already been described in a previous paper [1]. The main tank (volume of 50 L), in which a test tube heater is vertically mounted at one end of a transfer line (as shown in Fig. 1), is connected with a receiver tank through a transfer line with a control valve. The main tank is placed on a scale with 0.002-kg resolution. Forced flow is achieved by pressurizing the main tank to a desired value with pure hydrogen gas (99.99%) and adjusting the valve opening. The mass flow rate is estimated by the weight change and the flow rate of the feed hydrogen gas. The flow measurement error is estimated to be within 0.1 g/s [1].

The tube heater, which is made of stainless steel (SS316), has an inner diameter d of 6.0 mm, a length L of 200.0 mm and a thickness t of 0.2 mm. The outside of the tube heater is thermally insulated with a fiber-reinforced plastic (FRP) block. Both ends of the tube heater are electrically insulated by this FRP block. The heater has an entrance length of 75 mm, which is over ten times its diameter.

The electric resistance of the heater was measured using a double-bridge circuit. The double bridge circuit was first balanced at bath temperature. The output voltage of the bridge circuit (caused by the heater resistance deviation with the current heating), the voltage drop across the potential taps of the heater, and the voltage drop across a standard resistance were amplified at an interval of 30 ms. The average temperature of the heated tube, T_{av} , was estimated using the electrical resistance, which had been calibrated previously between 20 K and ambient temperature. The surface heat flux, q , was given as the difference between the heat generation rate, Q , and the time rate of change of energy storage. The average temperature of the inner heated surface, T_w , was calculated by solving the conduction equation in the

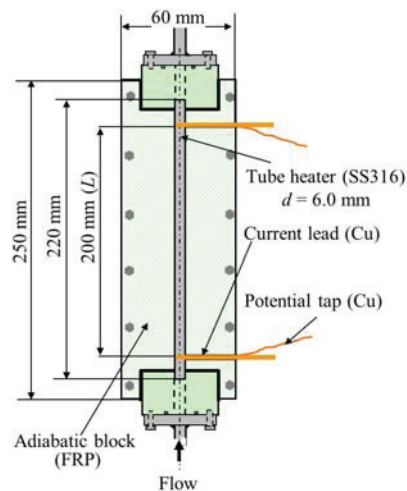


Fig. 1 Test tube heater

radial direction of the tube using T_{av} and Q .

The double-bridge circuit for measurement of the tube heater resistance has an accuracy of 1×10^{-4} , and a temperature deviation of about 0.1 K can be measured by the bridge. The bath temperature and the heater inlet temperature are measured by Cernox sensors with an accuracy of 10 mK. Only the temperature increment of the heater from the inlet temperature is necessary for the analysis. Accordingly, experimental error is estimated to be within 0.1 K for the heated surface temperature and 2 % for the heat flux [1].

Forced convection heat transfer from the inner side of the vertically-mounted long heated tube was measured at 0.7 MPa with a quasi-steady increase of the heat generation rate of $Q_0 e^{t/\tau}$ with $\tau = 10.0$ s; it had been confirmed experimentally that the heat transfer phenomena could be regarded as a continuous series of steady-states. The inlet temperatures, T_{in} , were varied from 20.8 K to the saturated temperature, T_{sat} , of 29.0 K. The flow velocities, v , were varied from 1 to 12 m/s.

3. Results and discussion

3.1. Typical forced convection heat transfer characteristics

The forced convection heat transfer characteristic for subcooled liquid hydrogen is shown in Fig. 2. The transverse axis indicates the excess heated surface temperature beyond the inlet temperature; $\Delta T_L = T_w - T_{in}$. With a quasi-steady increase in heat input, the heat flux gradually increases along the curves predicted by the Dittus-Boelter correlation [6] until nucleate boiling occurs. The heat transfer coefficient becomes increases at higher flow velocities. In the nucleate boiling regime, with relatively little increase in ΔT_L , the heat flux increases steeply up to a certain value, which is the DNB heat flux, q_{DNB} . Although the heat transfer of the developed nucleate boiling is independent of the flow velocity under the same subcooling condition, the DNB heat flux becomes larger at higher flow velocities. Above q_{DNB} , the heat transfer characteristic changes continuously to the film boiling regime, unlike that in a pool of liquid hydrogen [7]. This is because a vapor film would be formed downstream of the heated tube and gradually propagated the upstream.

3.2. DNB heat flux

Fig. 3 shows the DNB heat fluxes at a pressure of 0.7 MPa for various subcooling conditions and flow

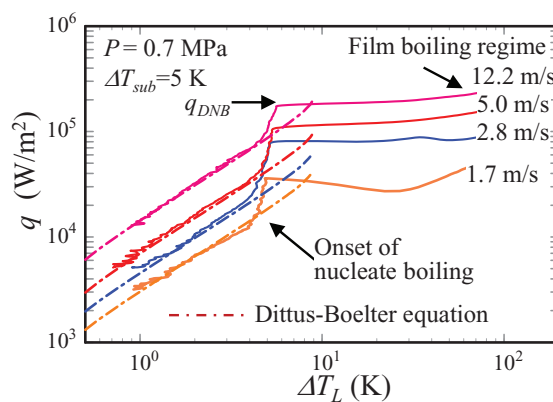


Fig. 2 Forced convection heat transfer characteristic of liquid hydrogen

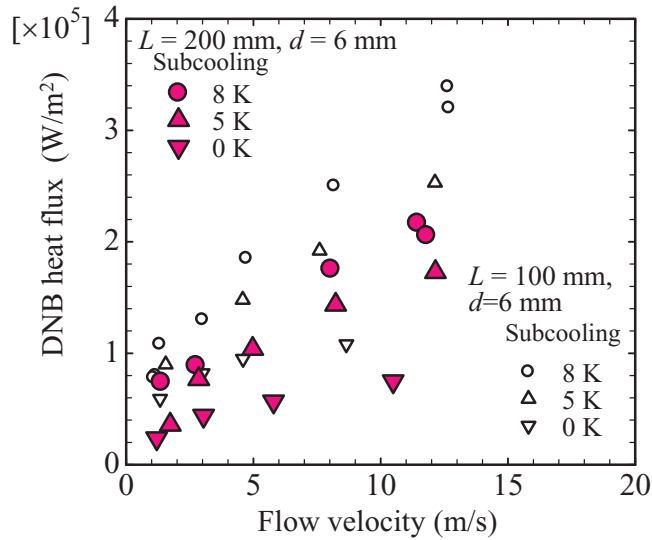


Fig.3 DNB heat fluxes at 0.7 MPa for various subcoolings and flow velocities.

velocities. The DNB heat flux increases for higher flow velocities and greater subcooling. For example, for $\Delta T_{sub} = 8.0$ K, the DNB heat fluxes are more than twice as large as those under saturated conditions ($\Delta T_{sub} = 0$ K). It seems that the heat transfer of subcooled liquid hydrogen is more significantly affected by the sensible heat transport contribution compared to that of subcooled liquid nitrogen [8].

3.3. DNB heat flux correlation

Shirai et al. [5] presented the following DNB heat flux correlation, expressed using the latent heat contribution and sensible heat contribution, based on their experimental data:

$$q_{sat} = Gh_{fg} (\rho_v/\rho_l)^{0.43} (L/d)^{-0.35} (0.32We^{-0.45} + 0.0017) \text{ for } We > 1700 \quad (1)$$

$$q_{sat} = 0.013Gh_{fg} (\rho_v/\rho_l)^{0.43} (L/d)^{-0.35} \text{ for } We \leq 1700 \quad (2)$$

$$q_{sub} = q_{sat} [1 + 4.3(\rho_v/\rho_l)^{-0.43} E^{-0.35} F_c Sc_{in}^{1.2}] \quad (3)$$

where q_{sat} is the DNB heat flux under saturated conditions, q_{sub} is the DNB heat flux under subcooled condition, $We = G^2 d \rho_l^{-1} \sigma^{-1}$, $Sc_{in} = C_{p,av} \Delta T_{sub,in} / h_{fg}$, $E = d(\sigma / g(\rho_l - \rho_v))^{-0.5}$, $C_{p,av} = \Delta h_{sub,in} / \Delta T_{sub,in}$, $F_c = \exp(-(L/d)/0.53Re^{0.4})$, We is the Weber number, Sc_{in} is the non-dimensional inlet subcooling, E is the non-dimensional heater diameter, F_c is the compensation factor for estimating the outlet subcooling, $C_{p,av}$ is the average specific heat, G is the mass flux, h_{fg} is the latent heat of vaporization, σ is the surface tension, g is the acceleration of gravity, ρ is the density, $\Delta T_{sub,in}$ is the inlet liquid subcooling, L is the heated tube length and d is the heated tube diameter.

In comparison, the measured DNB heat fluxes for a 10-mm long heated tube with the same diameter [2,4] are also shown in Fig.3. The DNB heat flux becomes smaller for a longer heated length. It decreases by around 30 % when the heated length is doubled. Therefore, it seems that the influence of L on the DNB heat flux is similar to $L^{-0.35}$ in Equations (1) and (2).

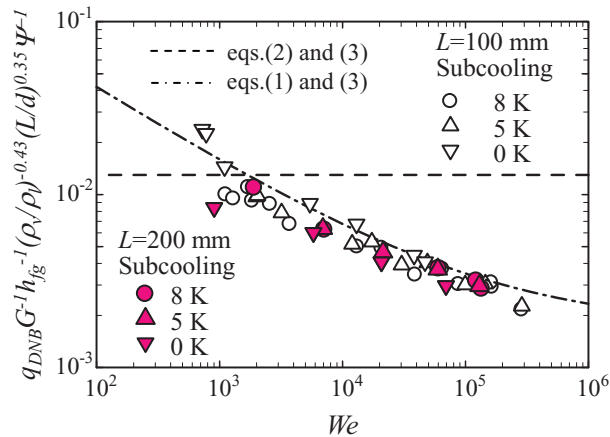


Fig. 4 Comparison of the measured DNB heat flux with the authors' correlation

A comparison of the measured DNB heat fluxes with the correlation is shown in Fig. 4, where the DNB heat fluxes are expressed as dimensionless values using Equations (1) and (3). The previous data for a 100-mm long tube are also shown in the figure. The experimental data are on an identical curve of $We^{-0.45}$. It is confirmed that the influences of L , the subcooling and the flow velocity can be described well by these correlations.

4. Conclusions

The heat transfer from the inner side of a vertically -mounted long tube with a diameter of 6.0 mm and a length of 200.0 mm to a forced flow of liquid hydrogen at a pressure of 0.7 MPa was measured for various flow velocities and inlet temperatures. The experimental results led to the following conclusions.

The heat transfer coefficients in the non-boiling region agree with the Dittus -Boelter equation. The non-boiling heat transfer coefficients are higher at higher flow velocities.

The DNB heat flux increases with increasing subcooling and flow velocity. It seems that the heat transfer of subcooled liquid hydrogen is significantly governed by the sensible heat transport contribution. With an increase in the heated length, the DNB heat flux becomes smaller. The rate of decrease is similar to $L^{-0.35}$ as in the DNB correlation given by Shirai et al. [5]. It is confirmed that the DNB correlation can describe not only the effects of the subcooling and the flow velocity but also of L .

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